TIME DOMAIN™

THE NEW WIRELESS MEDIUM™

Appendix A

TIME MODULATED ULTRA-WIDEBAND TECHNOLOGY

TECHNOLOGY BASICS

TDC's TM-UWB transmitters emit ultra-short "Gaussian" monocycles with tightly controlled pulse-to-pulse intervals. TDC has been working with monocycle pulse widths of between 1.50 and 0.20 nanoseconds (billionths of a second) and pulse-to-pulse intervals of between twenty-five and one thousand nanoseconds. These short monocycles are inherently ultra-wideband.

The systems use pulse position modulation. The pulse-to-pulse interval is varied on a pulse-by-pulse basis in accordance with two components: an information signal and a channel code.

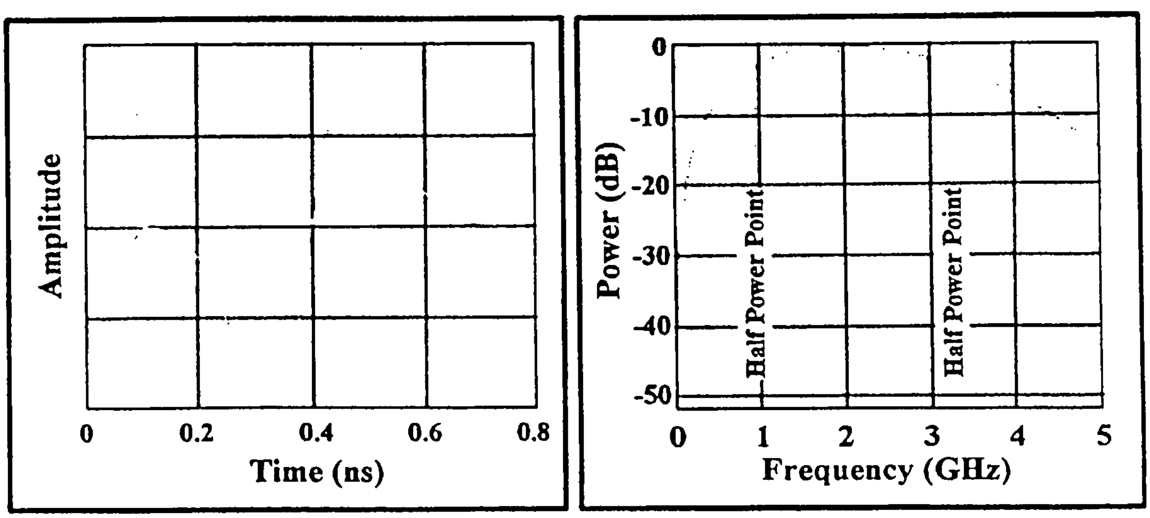
The TM-UWB receiver directly converts the received RF signal into a baseband digital or an analog output signal. A front end cross correlator coherently converts the electromagnetic pulse train to a baseband signal in one stage. There is no intermediate frequency stage, greatly reducing complexity.

A single bit of information is generally spread over multiple monocycles. The receiver coherently sums the proper number of pulses to recover the transmitted information.

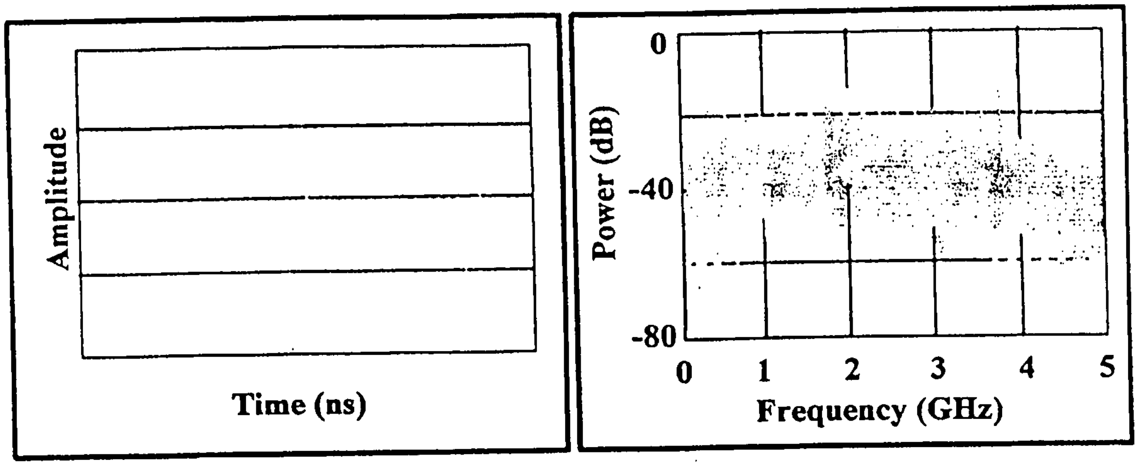
GAUSSIAN MONOCYCLE

The most basic element of TDC's impulse radio technology is the practical implementation of a Gaussian monocycle. Figure 1 shows the monocycle in both the time and frequency domains.

2 GHz Center Frequency Gaussian Monocycle in Time and Frequency Domains
Figure 1



A Monocycle Pulse Train In The Time and Frequency Domains
Figure 2

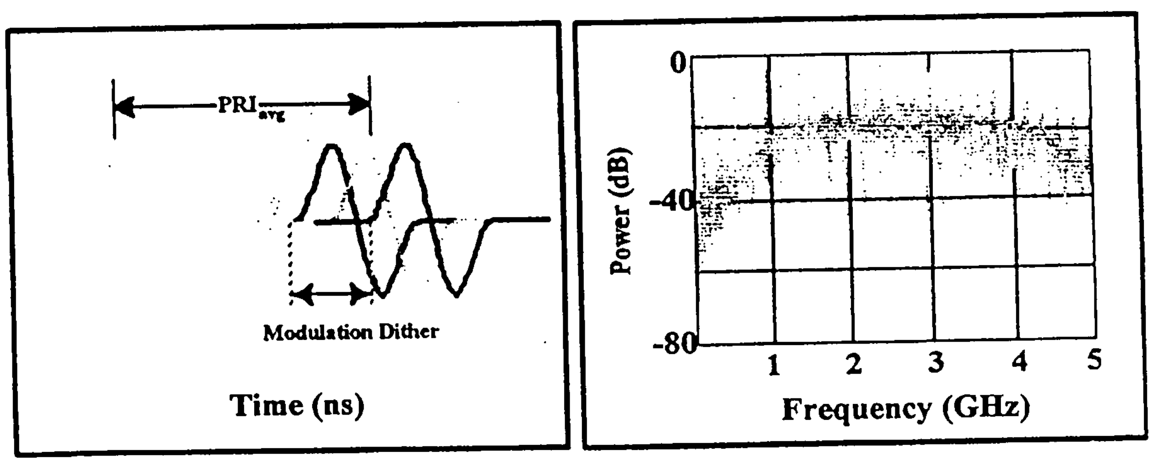


MODULATION

Additional processing is needed to modulate the monocycle pulse train, so the system can actually transmit information.

TDC's systems use pulse position modulation as this technique allows the use of an optimal receiving matched filter technique. TDC's receivers use a cross-correlator that gives the homodyne receiver the ability to find the signal well below the ambient noise level.

Pulse Position Modulation
Figure 3



As illustrated in Figure 3, pulse position modulation varies the precise timing of transmission of a monocycle about the nominal position. For example, in a 10 Mpps system, monocycles would

be transmitted nominally every 100 ns (represented in Figure 3 as the time period PRI_{avg}). In such a system a "0" digital bit might be represented by transmitting the pulse 100 ps early and a "1" digital bit by transmitting the pulse 100 ps late.

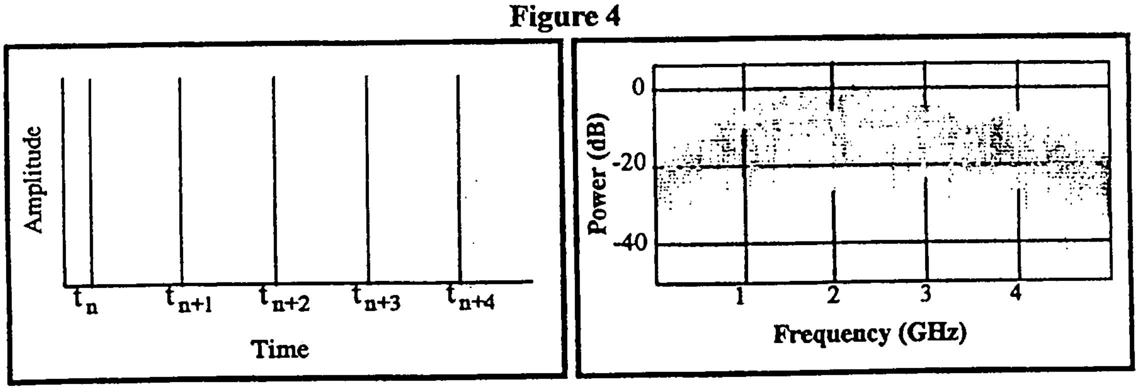
As shown in the right hand graph in Figure 3, pulse position modulation distributes the RF energy more uniformly across the band (it "smoothes" the spectrum of the signal), thus making the system less detectable. However, because information modulation only moves the pulses only a fractional part of a pulse width, this spectral smoothing impact is small.

PSEUDO-RANDOM NOISE CODING

Coding for channelization

At this point, any modulated pulse train looks like any other pulse train; it is not channelized. However, by shifting each monocycle's actual transmission time over a large time frame in accordance with a code one can channelize pulse trains. As illustrated in Figure 4, TDC applies a relatively large time offset (many nanoseconds) to each impulse. TDC uses "pseudo-random noise" codes ("PN codes") for this purpose. In a multiple access system, each user would have their own pseudo-random noise code sequence. Only a receiver operating with the same pseudo-random noise code sequence can decode the transmission.

The Impact of Pseudo-Random Time Modulation on Energy Distribution in the Frequency Domain
Figure 4



In the frequency domain, this pseudo-random time modulation make TDC's signal appear like pure white noise. As a result, anyone without knowledge of the PN code, attempting to detect the presence of the signal would have to be very close to the transmitter and even then would be unable to decode the transmission without significant effort.

RECEIVING MONOCYCLE TRANSMISSIONS

Having generated a signal with minimal spectral features, it is also necessary to have an optimal receiving system so that the power that must be transmitted is also minimized. The optimal receive technique, and the technique used in TM-UWB, is a correlation receiver ("correlator"). A

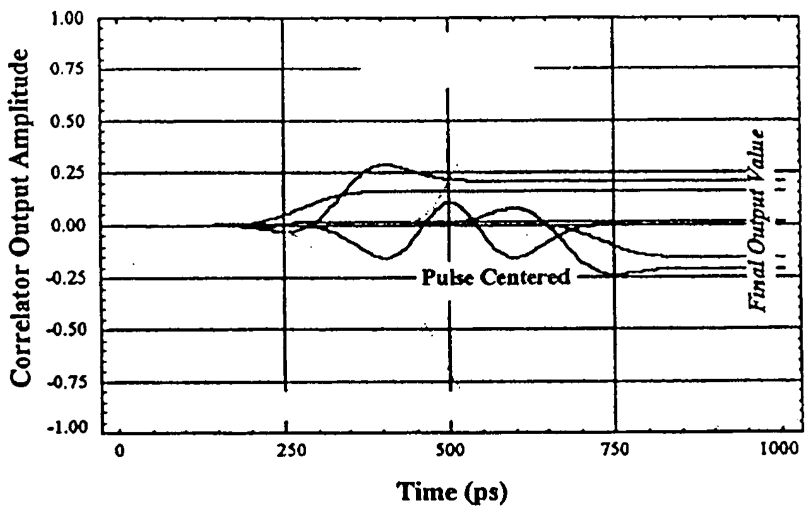
correlator multiplies the received RF signal with a "template" waveform and then integrates the output of that process to yield a single DC voltage. This multiply and integrate process occurs over the duration of the pulse and so it also occurs in less than a nanosecond.

With the proper template waveform, the output of the correlator is a measure of the relative time positions of the received monocycle and the template. Figure 5 shows the output of the correlator that corresponds to different time offsets between the template and the received waveform.

As shown in Figure 5, the correlator is an optimal early/late detector. When the received pulse is ¼ of a pulse early, the output of the correlator is a −1; when it is ¼ of pulse late, the output is +1; and when the received pulse arrives centered in the correlation window, the output is zero.

It is critical to note that the mean value of the correlator is zero. Thus, for in-band noise signals received by a TM-UWB the correlator's output value has an average value of zero. Moreover, the standard deviation (RMS) of the correlator output is related to the power of those in-band noise signals.

Correlator Output
Figure 5



When a monocycle is buried in the noise of other signals, it is impossible to detect the reception of a single TM-UWB pulse. However, by adding together numerous correlator samples, it becomes possible to receive transmitted signals. This process is called "pulse integration." Through pulse integration TM-UWB receivers can acquire, track and demodulate TM-UWB transmissions that are significantly below the noise floor. The measure of a TM-UWB receiver's performance in the face of in-band noise signals is processing gain.

Processing Gain and Jamming Resistance

Pseudo-random and random time modulation when combined with the correlator make time modulated radios and radars highly resistant to jamming from all radios. This is critical as all other signals within the band occupied by an time modulated signal act as jammers to the time modulated radio and, since there are no unallocated 1+ gigahertz bands available for time modulated systems, time modulated radios will have other signals within their operating band.

Processing gain is a measure of a radio's resistance to jamming. Time modulated radios have huge processing gain.

One definition of processing gain is the ratio of the bandwidth of the signal to the bandwidth of the information signal. For example, Qualcomm's spread spectrum system with a 8 kHz information bandwidth and a 1.25 MHz channel bandwidth yields a processing gain of 156 (22 dB). An impulse system transmitting the same 8 kHz information bandwidth and a 2 GHz channel bandwidth the processing gain is 250,000 or 54 dB.

Alternatively, the process gain for an impulse signal may be calculated from:

- The duty cycle of the transmission, e.g., a 1% duty cycle yields a process gain of 20 dB.
- The effect of pulse integration, e.g., integrating energy over 100 pulses to determine one digital bit yields a process gain of 20 dB.
- The total process gain is then the sum of these two components, e.g., 40 dB.

A 2 GHz / 10 Mpps link transmitting 8 kbps would have a process gain of 54 dB, because it has a 0.5 ns pulse width with a 100 ns pulse repetition interval = 0.5% duty cycle (23 dB) and 10 Mpps / 8,000 bps = 1250 pulses per bit (another 31 dB).

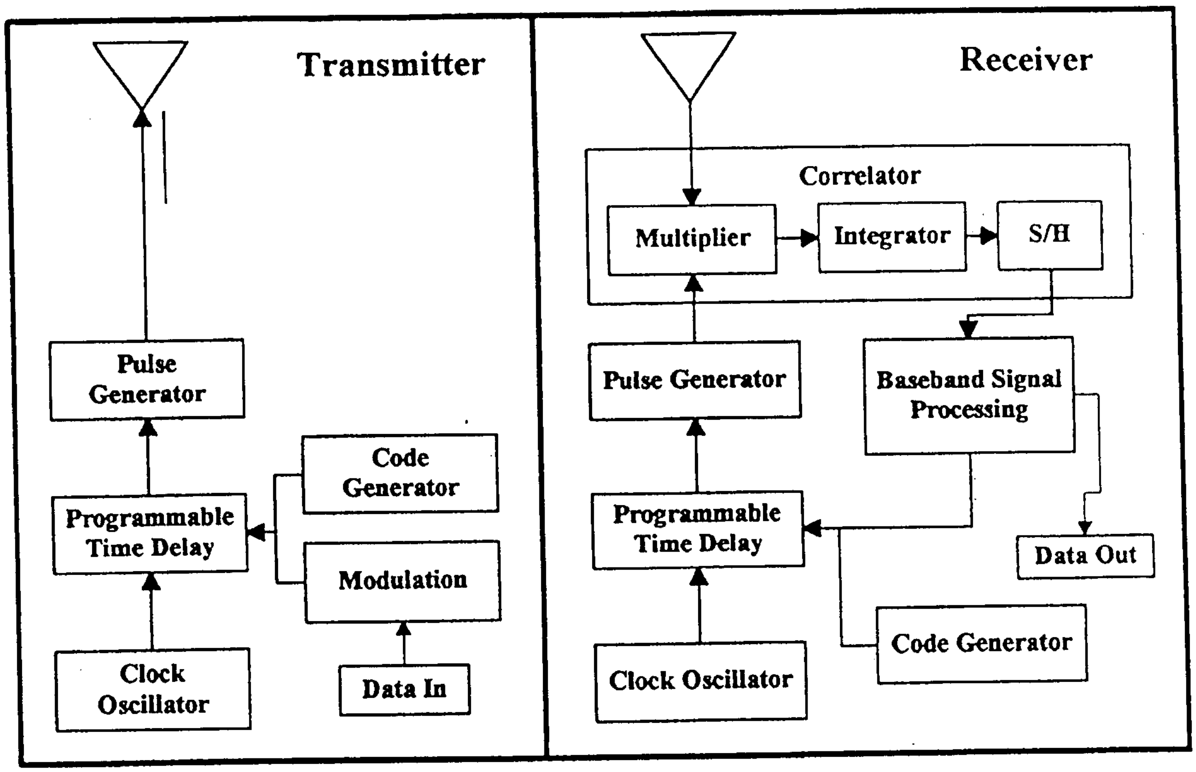
BLOCK DIAGRAM

Figure 6 is a high level block diagram of both a TM-UWB transmitter and receiver. As shown, the transmitter does not contain a power amplifier as the transmitted pulse is generated by a pulse generator at the requisite power. A critical part of the pulse generation circuit is the antenna, which acts as a filter.

The receiver resembles the transmitter, except that the pulse generator feeds the multiplier within the correlator. Also, baseband signal processing must extract the modulation and control signal acquisition and tracking.

The blocks in red have been implemented as full custom silicon germanium ICs. The blocks in green can be implemented in standard CMOS.

Block Diagram
Figure 6



SYSTEM CAPACITY

A theoretical analysis[1], conducted for TDC by University of Southern California Professor R.A. Scholtz suggests that TDC's impulse radio system could have thousands of voice channels per cell without special signal processing algorithms. Others have analyzed the system, and using more realistic assumptions, estimate the capacity to be between 200 and 1000 simultaneous duplex 64 kbps telephone conversations per base station, depending upon numerous environmental factors and also without special signal processing algorithms.

Using a cellular architecture and standard radio engineering practices, e.g., sectorized base station antennas, TDC can achieve even higher densities of simultaneous users.

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[1]See: R.A. Scholtz, "Multiple Access with Time-Hopping Impulse Modulation" (invited paper), MILCOM'93, Bedford, MA, Oct. 11-14, 1993.

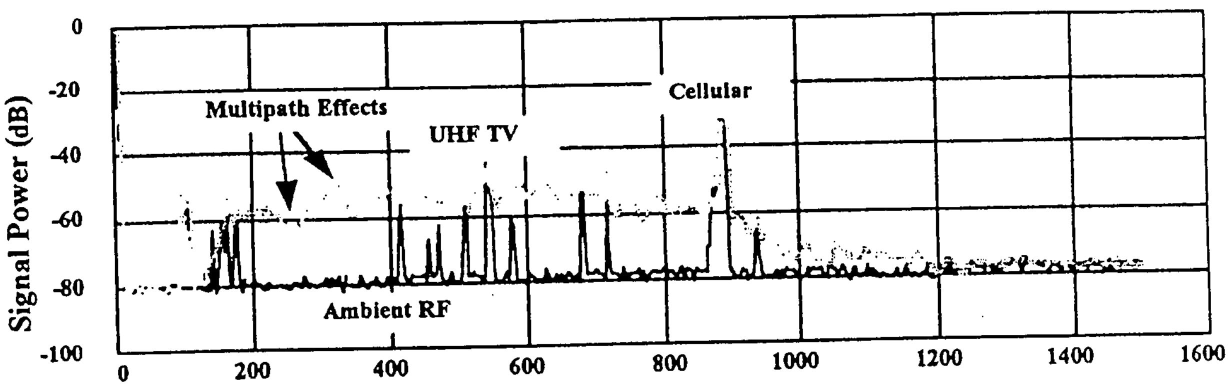
PERFORMANCE IN THE REAL WORLD

TDC'S TEST SYSTEMS

Time Domain has built numerous prototypes. The prototypes include simplex and duplex communications systems and short range radars. Early prototypes were constructed of discrete off-the-shelf components. However, Time Domain is now using full custom silicon-germanium integrated circuits to perform the functions of the RF correlator circuitry and the timing subsystem. The programmable time delay IC parses time to 3 ps steps.

675 MHz Impulse Signal At 3 Meters*

Figure 7



*Measurements not adjusted to compensate for antenna performance.

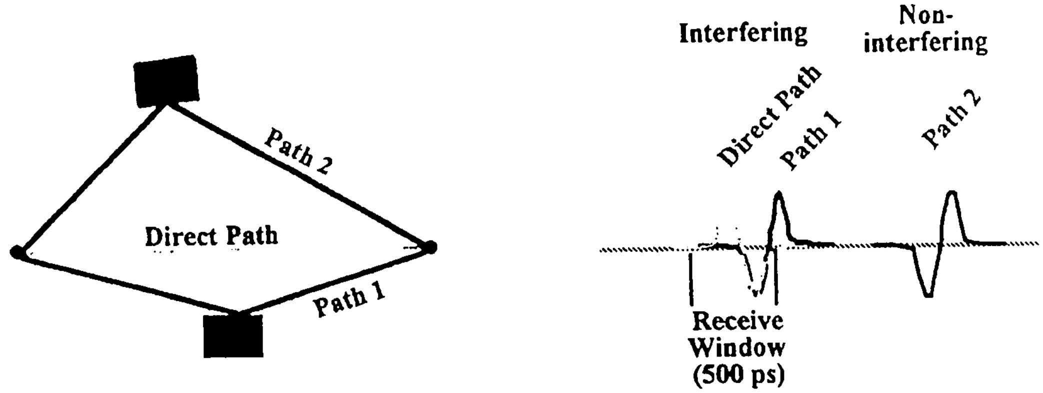
An early prototype built by TDC has an average radiated power of 450 μW. The center frequency is 675 MHz. Figure 7 shows the signal measured at 3 meters, as well as ambient signals. (The "bumpiness" of the TM-UWB spectrum reflects the impact of multipath. Moving the receive antenna around causes the location of nulls and peaks to move. This does not impact the performance of the impulse system. See "Multipath and Propagation" below.

In October 1997 Time Domain demonstrated a 1.7 GHz TM-UWB full duplex radio with an RF bandwidth in excess of 1.3 GHz. The output power was approximately 1.8 mW. At 32 kbps, the link range was in excess of 900 meters. Recent improvement to the design have integrated simultaneous radio ranging with a resolution of 0.1 foot and improved communications range substantially.

MULTIPATH AND PROPAGATION

Rayleigh, or multipath fading, so noticeable in cellular communications, is a continuous wave phenomenon. Multipath fading is not a problem for time modulated systems.

Multipath In An Impulse System
Figure 8



In a time modulated system, in order for there to be multipath effects, one of two conditions must persist. Either:

- The path lengthtraveled by the multipath pulse must be less than the pulse width times the speed of light. For a one nanosecond pulse, that equals 0.3 meters or about 1 foot, i.e., [1 ns] x [300,000,000 meters/second]. (See Figure 8); or
- The multipath pulse travels a distance that equals the interval of time between pulses times the speed of light might interfere times an integral number with the next pulse. (For a 1 Mpps system that would be equal to traveling an extra 300, 600, 900, etc. meters.) However, because each individual pulse is subject to the pseudo-random time modulation, these pulses are decorrelated.

Monocycles traveling between these intervals do not cause self-interference (in Figure 8), this is illustrated by the monocycle traveling Path 2). While pulses traveling grazing paths, as illustrated in Figure 8 by the narrowest ellipsoid, create impulse radio multipath effects.

Time Domain Measurement of 1.3 GHz Impulse Signal at 8 Meters
Figure 9

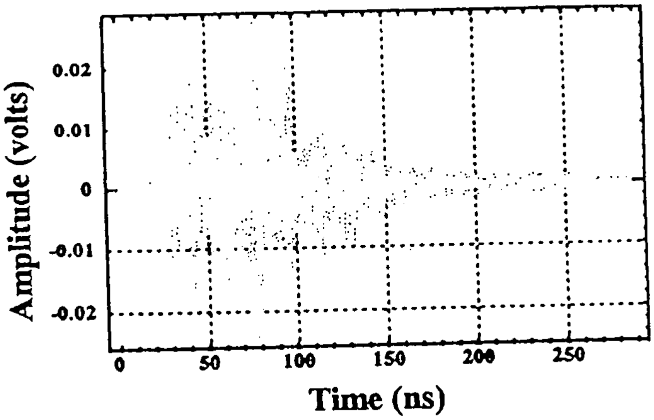


Figure 9 shows how easily a time modulated radio can resolve multipath. These measurements were made in a standard commercial office building. The transmit and receive antennas were 8 meters apart with three interior wall between them. These walls were constructed of steel studs and plaster board.

As can be seen in Figure 9, the environment disperses a sub-one nanosecond pulse over at least one hundred nanoseconds. In the frequency domain, this becomes Rayleigh fading; however, for TM-UWB radio, each of these reflections is an independent signal that can be received.

Channel models of TM-UWB signals do not exist. The difficulty is that such models must be developed using time domain data with at least several hundred picosecond resolution. At present this can be accomplished only at short ranges (less than 500 meters) with existing test equipment and only then under ideal circumstances. Time Domain is now constructing an instrument that will be able to measure the impulse response of the environment with sub-ten picosecond resolution. Data from this instrument will resemble the data in Figure 9, but over much longer time scales (microseconds if necessary). With such an instrument Time Domain expects to characterize TM-UWB channels many different environments. Such models will characterize for example the number of signal paths available, their power distribution, etc.

SIMPLICITY

TDC's time modulated radios are much simpler to build than equivalently sophisticated conventional radios.

The transmitter is much simpler than a narrowband transmitter, it is simply a single transistor that operates in a digital mode – it flips from a "0" state to a "1" state, this transition produces a step waveform that can be easily filtered to produce a monocycle. Thus, unlike conventional transmitters it does not contain a linear amplifier. This reduces cost and power consumption.

The receiver is also simpler than a narrowband receiver as it does not require IF stages. And unlike spread spectrum receivers, the control loop operates at very low frequencies, which also saves cost.

Preliminary studies suggest that a time modulated transmitter and receiver front end can be build on a single chip. TDC sees no impediments to producing an impulse radio and radar systems that could sell for less than $200.

SUMMARY

TDC's impulse radios have far superior performance in high multipath environments than narrowband radios, including spread spectrum technologies. Multipath is a critical problem for most radio system because people live in environments where there are lots of objects that reflect radio signals. In these environments, time modulated radios can operate at high data rates with lower bit error rates and with lower transmit powers than conventional radios.